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Impact of power sharing method on battery life extension in HESS for grid ancillary services

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***Abstract*—Hybrid energy storage system (HESS) based on Li-ion and supercapacitor (SC) can play a potential role to stabilise the grid by providing the fast frequency ancillary services. The SC helps to reduce the battery charge/discharge stress and hence assists to extend the battery lifespan. The power sharing method (PSM) is the heart in control part to improve the HESS performance and reduce the battery stress. This paper proposes a hybrid PSM and investigates its impact on battery life extension along with its relation to the system design and regulation signal. The performance of hybrid PSM is compared with three other PSMs (low pass filter, first and second rule based) in a 10 MW / 10 MWh full-active parallel HESS for frequency regulation service in two networks: UK (national grid) and USA (PJM). Considering maximum possible battery lifetime upto 25 years, result shows that the hybrid PSM approach allows a degree of better performance for both grid while the sharing of SC is kept maximum 2.0% and 2.5% (for US and UK grid respectively) of the HESS capacity. This study also analyses the impact of PSM on shared capacity and design of HESS for different grid regulation signals.**

***Index Terms*—Ancillary services, fast frequency response, hybrid energy storage system, power sharing, battery lifespan.**

I. Introduction

The increasing demand for electricity and target for CO2 emission reduction boost the penetration of renewable energy (RE) to the national grid network. However, the integration of RE technologies have also negative impact on the grid power quality and cause grid instability [1], [2]. To deal with such challenge by improving the grid stability for high penetration of renewable, an increasing interest is given to provide grid ancillary services through the deployment and efficient control of electrical energy storage system (ESS) [3], [4]. This technology provides many services to the electricity network and presents an inherent solution to overcome the intermittent characteristics of RE resources [5], [6]. Now-a-days, to deal with the grid stability issues, such as, the primary frequency control and to improve the rate of change of frequency (ROCOF) index, the regulation service providers are paying attention on battery based energy storage system (BESS). This technology is considered to be matured and efficient, thanks to its power and energy density characteristic and fast response time [7]–[9]. However, the batteries are still costly, and their use for high frequency regulation signal compensation can cause a rapid damage/degradation of their lifetime [8].

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To overcome this problem, the hybrid system that combines different types of storage systems, presents itself as a potential solution to deal with the fast frequency responses for the regulation signal. In most cases, battery (such as lead acid, Li-ion with high energy density) and some other type of energy storage (such as super-capacitor, flywheel etc with high power density and very fast response) systems are integrated in different topologies to form a hybrid energy storage system (HESS) [10], [11]. This combination is done mainly to develop an advanced energy storage system with high power and energy density to work together in very short and long time domain [12], [13]. Along with the service, this type of hybrid solution protects the battery from rapid degradation which in turn increases the overall system efficiency and thus may improve the condition of financial sustainability [14]–[16]. Literature review shows that the battery and super-capacitor based HESS is one of the most promising hybrid techniques which has the high potential in grid/renewable energy application [6], transportation [17], [18], and frequency regulation services [8], [19]. The speciality of high power density and fast response dynamic characteristics drive the SC as a potential storage solution in high power applications [5]. However to deal with a combined high power high energy application, the SC is generally associated with another high energy density ESS and, in such case, it handles the transient/high frequency component of the HESS power output efficiently [19], [20].

The efficient performance of HESS depends on the integration topology, system design (sizing the system components) and the control (especially on power sharing method). The integration topology is very important in optimizing the system performance and reducing the battery charging/discharging stress, thus extending the battery lifespan [8], [21]. Different topologies (such as passive, semi-active, full-active) are already being studied and investigated for many industrial applications [22]. It is found that in parallel full active configuration, the storage devices can be operated/controlled independently and thus has more technical advantages over the other topologies. Therefore, it is chosen as the most favorable topology especially for providing grid ancillary services [8]. Moreover, the power sharing method (PSM) also plays a critical role in system design and optimizing the system performance, maximizing the lifespan of the energy storage and protecting the system components from severe operating condition [18]. Finally, it helps to maximize the techno-economic benefits of the system [5].

Several techniques of PSM for HESS have been proposed in the literature for different industrial application as elec-

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tric/hybrid vehicle [18], [23], railways traction [17], [24], [25], renewable generators [26], [27], grid and microgrids [13], [21]. They can be split into two main categories. The first one includes heuristic approach such as filtration based (low /high pass filter) [28], [29], rule based (RB) [6], [17], [18], [27], [30], fuzzy and neuro-fuzzy logic [26], [31], and droop control based [32]. This type of PSM doesn't rely on optimal design, however, it presents acceptable performances and can be implemented in real time application. The second category deals with PSM optimal investigation while considering an objective function. These kinds of optimal controllers are considered to be model-based approaches and can be divided into instantaneous and offline methods. The instantaneous one can be implemented in real time as a model predictive control approach [33]. However, the offline methods are based on finite-horizon optimization. A variety of offline methods are found in the literature, such as particle swarm optimization [34], [35], genetic algorithm [36], dynamic programming [17], [37], Pontryagin' minimum principle [17], convex programming [10], wavelet-based multi-objective method [23]. It is worth mentioning that in addition to their heavy computing, finite-horizon methods require a prior knowledge of reference power output of the HESS system. This can be achieved only in some applications such as vehicles and railways through the prior knowledge of driving cycle, or in some PV/wind-grid/microgrid application where the irradiance and/or the wind profile are known/estimated. Table I presents some PSM methods and their applications, and it is found that no optimal approach is applied for frequency grid response services (as RegD or EFR) since the regulation signal can neither be predicted nor estimated.

TABLE I
EXEMPLES OF PSMS AND THEIR APPLICATIONS

Area of Application	Heuristic PSM	Optimal PSM
EV/EHV	[17], [38]	[17], [34]
Railways	[18], [24]	[25], [39]
Grid / Microgrid / Renewable	[6], [28], [31]	[35], [36], [40]
Frequency Response (EFR, RegD...)	[8], [32]	—

It is to be noted that most of the PSM methods previously discussed are applied to improve the overall system performance. Few of these, discuss the importance/impact of the method on extending the battery lifespan. In [28], the authors have shared the battery power with a super-capacitor for a small scale wind power system to operate in off-grid condition. It is observed that the battery life can be extended upto 19% by implementing a modified low pass filtering (LPF) PSM. In [29], the authors expand the application of a HESS based on SMES-battery (with a novel battery lifetime model) to provide frequency support for an off-grid wind energy system. In this case, LPF based PSM further reduces the depth of discharge (DOD) variation of the battery and thus it allows to increase the battery lifespan by a 32% compared to its base case. In [27], authors have shown how the simple RB approach can improve the performance of BESS management which smooths the dispatching from intermittent renewable sources. In [30], authors have applied the RB approach to analyze the performance of battery and supercapacitor (SC) based HESS system for mitigation of pulse loads in hybrid microgrid system. The RB approach also has been applied in grid connected large solar power plant [6] and tramway [18]. All of these papers have rarely discussed the impact of RB PSM on the extension of the battery lifespan. In [34], the authors have combined the rule based and the particle swarm optimization techniques to run an electric vehicle more efficiently. It is found that 20% increase of battery lifespan can be achieved with this hybrid PSM in hybrid system. The authors in [32] have also shown that the battery lifespan can be even extended around 62% while using dynamic droop method for primary frequency control in an isolated microgrid system.

It is worth noting that from the technological solution point of view, battery-SC based HESS are getting more importance for dynamic or fast response services. Review also shows that the developed PSMs were tested for a single HESS system with predefined storage capacities (both for battery and SC) and also for the same reference signal (hybrid vehicles, regulation signals etc.). The application of HESS for fast frequency ancillary services are relatively new and has high potential market. Thus, many research questions are arising and we need to address these. Such as:

(i) do the PSM maintain the same performance for different dynamic characteristics or different reference signals?

(ii) do the PSM have effect on hybridization factor (% of SC capacity) in the storage system?

(iii) how the reference signal, PSM and hybridization factor impact on the effective cycle of the battery to extend its lifespan?

The answer to these questions will help to identify the possible best PSM and hybridization factor in HESS for its application. As the share of SC capacity influences the cost of the system, this will ultimately impact on the techno-economical sustainability of the system.

Therefore, in response to these questions, this study is to investigate the impact of the PSM on battery life extension and its relation with the system design, hybridization factor and the regulation signal characteristics. A hybrid PSM is also proposed in the study which is a combination of LPF and RB approach. The performance of this hybrid PSM is then compared with LPF and two types of RB approaches in a 10 MW / 10 MWh HESS (based on Li-ion battery and super-capacitor) for frequency regulation service in two types of network from UK (national grid) and USA (PJM). The first signal considers the enhanced frequency response (EFR) of the UK grid and the second one deals with the PJM dynamic regulation (RegD) signal from USA network. The design and modeling of the storage elements for HESS are explained in section 2. The control and power management of HESS are briefly described in section 3. Section 4 deals with the strategies and algorithms of the implemented PSMs. Simulation and case studies are discussed in section 5 where comparative study on the performance of PSMs are analyzed to understand the impact of PSM on battery life extension for ancillary services. Concluding remarks are made in section 6.

II. Design and modeling of the storage elements

In HESS, the system is classified based on the placement and connection topologies of the storage devices. These can be termed as passive, semi-active, full-active and modular type HESS [8], [22]. Some comparative performance studies of these topologies for different industrial applications are also found in [21], [34]. The main difference between these topologies consists of the use and placement of power electronics converters (DC/DC and DC/AC) to share and control the power flow between the storage units and the grid. For grid regulation (ancillary) services, the authors in [8] have compared the passive, semi-active, and parallel full-active topologies of battery-SC based HESS. Regulation signal from PJM [41] is chosen for the analysis and concluded that the full-active configuration should be the best option to maximise the system efficiency where both the battery and SC systems are isolated by the converters and controlled to operate independently. Taking into account the aforementioned remark, we consider full-active HESS for this study.

The combination of Li-ion and SC presents one of the most widely used hybrid solutions to enhance the functionality of HESS [18], [21], [32]. Compare to other types of battery, the Li-ion benefits the system with good efficiency indices and high energy density. The SC is also well known for its high power density with fast charging/discharging characteristics and this allows it to deal with the high frequency regulation signals more efficiently. In case of HESS for grid services, this advantage then significantly reduces the charging/discharging stress of the battery and thus allowing an extension of the lifespan.

Fig. 1 shows the simple power sharing process of HESS system. The reference power for each of the storage elements is designed according to the characteristic of the regulation signal and the transmission system operator (TSO) requirement. The control method/strategy for power sharing ultimately helps to determine the required capacity of the storage elements.

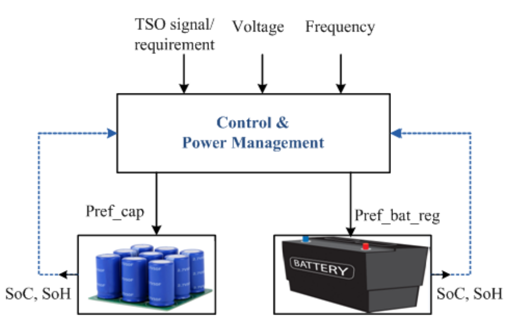

Fig. 1. Simple power sharing process of HESS system .

To understand the impact of PSM on different dynamic characteristics of the network and the sharing capacity of SC, we have considered the HESS with a total capacity of 10 MW / 10 MWh for frequency regulation service in two types of networks from UK (national grid) and USA (PJM). Initially, the capacity of each storage components is defined according to the hybridization percentage p such that:

$$C_{HEES} = C_{cab} + C_{bat}$$

$$C_{cab} = pC_{HEES}$$

where C_{bat} and C_{cap} are the capacity of the Li-ion battery and the SC module respectively.

Considering the practical implementation case, SC pack is configured such that 100 SC are connected in series and the number of parallel packs are chosen according to the total capacity of the SC bank (based on hybridization percentage, p). A 3400F Maxwell UltraBlue SC model is used which is characterized by a 2.85v nominal voltage. Thus, the nominal voltage of the SC bank is 285v. Similarly, Lion-ion battery is composed of parallel pack units with 200v nominal voltage. It is noted that the proper modeling of storage components for simulation has huge impact on evaluating the system performance and this is due to the strong relationship among the HESS storage components, its power sharing and energy management system. Very specifically, modeling of charging and discharging characteristics of the storage components and its proper control play the vital role in this analysis. Hence, this section discusses the modeling of these charging/discharging of battery and the SC module.

A. Li-ion Battery model

The Li-ion battery is modeled using equivalent circuit approach, as presented in [42]. In case of discharging mode, the output voltage of the battery (V_{bat}) is expressed as follow:

$$V_{bat} = R_b I + f_1(it, i^*, i) \tag{1}$$

$$f_1(it, i^*, i) = E0 - K\frac{Q_b}{Q_b - it}i^* - K\frac{Q_b}{Q_b - it}it + Aexp(-Bit) \tag{2}$$

For charging mode, V_{bat} is given as:

$$V_{bat} = R_b I + f_2(it, i^*, i) \tag{3}$$

$$f_2(it, i^*, i) = E0 - K\frac{Q_b}{0.1Q_b + it}i^* - K\frac{Q_b}{Q_b - it}it + Aexp(-Bit) \tag{4}$$

E_{Batt} is the nonlinear voltage, E_0 presents the constant voltage and, $exp(s)$ presents the exponential zone dynamics. K is polarization constant. i^* and i presents respectively the low frequency current and the dynamics battery current. it is the extracted capacity and Q_b denotes the maximum battery capacity. A and B are respectively the exponential voltage and the exponential capacity of the battery.

In any battery based storage application, the considered End of Life (EoL) is an important parameter to decide the replacement time/period for the battery. In most of the cases, it is found that the batteries are replaced when the effective total capacity of the battery falls around 20% of its initial value [43]. The reasons that influence this degradation are due to the battery chemistry itself, its charging/discharging characteristics, how frequent of meet the ramp up conditions, operating temperature, maintenance regime etc. Battery aging model to estimate the state of this health condition of the battery are well developed in the literature. In this paper, an Ah-degradation model is considered [8] due to its especial attention on the effective number of throughput cycles (N_{eff}) and the depth of discharge (DOD) stress factor.

To account both discharge and charge currents, N_{eff} is expressed as:

$$N_{eff} = \int \frac{|I(t)|\,dt}{2Q} \tag{5}$$

where Q denotes the nominal charge capacity of battery and $I(t)$ presents the instantaneous battery current value. A lower value of N_{eff} represents the increase of battery lifetime. In addition, in order to account the impact of SOC variation range, the number of completed full cycle of a battery depends on the N_{eff} and the DOD operating range $\theta(0\% < \theta < 100\%)$ [8]. As an example, a 50% DOD battery opertaing range allows to reduce by 50% the degradation that a full 100% DOD operating range can cause.

B. Supercapacitor Model

The model of SC is developed on the basis of Stern model as presented in [42]. The SC output voltage is expressed as:

$$V_{SC} = \frac{N_s Q_T d}{N_p N_e \varepsilon \varepsilon_0 A_i} + \frac{2N_e N_s RT}{F} sinh^{-1}\left(\frac{Q_T}{N_p N_e^2 A_i \sqrt{8RT\varepsilon\varepsilon_0 c}}\right) - R_{SC} i_{sc} \tag{6}$$

$$Q_T = N_P Q_c = \int i_{sc} dt \tag{7}$$

where i_{sc} is the SC module current. $i_{self-dis}$ represents the self-discharge phenomenon, Ai and c are respectively the interfacial area between electrodes and electrolyte, and the molar concentration. r is the molecular radius and F denotes the Faraday constant. Vsc is the SC output voltage and N_e and N_A are respectively the number of layers of electrodes and Avogadro constant. R denotes the ideal gas constant, d is the molecular radius and T is the operating temperature. ε and ε_0 are the permittivity of material and free space respectively.

III. CONTROL AND POWER MANAGEMENT OF HESS

The overall control and power management of HESS depend on the performance of the three main components: reference power computing, power sharing and battery SoC control, as shown in Fig. 1.

Generation of accurate reference power $Pref$ for providing ancillary services is the very first task of the controller. This is generated according to the type and characteristics of the provided regulation signal. For example, EFR is implemented in UK (national grid). For this purpose, a real time frequency data from the point of interest in the grid network is taken into consideration. Droop method is then applied to the signal, considering the service window as set up by the TSO, to compute the (pu) reference signal. This signal is then multiplied by the nominal power (P_n) of the HESS system to compute the reference output power signal [7].

In case of US grid, PJM generates a dynamic regulation signal and transmits to the regulation service provider in every 4s. This signal is then scaled down by a factor to generate the reference regulation signal for the HESS according to its regulation capacity [8].

Depending on the implemented "power sharing method (PSM)", the generated reference signal is then divided into two reference signals for the battery and SC system. As the study is to understand the impact of the PSM on the battery life extension, therefore the implemented PSMs are discussed in a separate section of this paper.

Finally, the battery SoC controller allows to adjust the reference power for the battery in order to maintain the state of charge (SOC) as close as possible to the reference value. To achieve this, a PI-based control method is considered in this manuscript. The basic structure includes a PI controller and a dead zone block which are used to minimize the battery use whenever the SoC value is within a certain range $\left(SoC_{ref} - SoC \in \begin{bmatrix} -SoC_d & SoC_d \end{bmatrix}\right)$. The parameters of the PI controller (KP_{SoC} and KI_{SoC}) are chosen to optimize the regulation capacity of the battery. The output of the PI controller should be adjusted to deal with the TSO requirement. For EFR service, a dynamic saturation block is designed according to the signal portfolio [7], [44] (Fig. 2a). However, in case of RegD, a simple saturation block is implemented to maintain the regulation signal within a certain value such that the regulation required power $|P_{bat-reg}| < \delta_{bat-reg} P_n$, where P_n is the nominal power of the system and $\delta_{bat-reg}$ is the maximum percentage of the required regulation power by the battery (Fig. 2b).

The first and third blocks of the control and management of HESS are usually designed to fulfill the regulation signal requirements that are defined by the TSO. They are considered for battery only storage system. In case of HESS, PSM should also be considered and an engineering approach to the optimal design has to be assessed.

IV. POWER SHARING METHOD (PSM)

The PSM is one of the most important blocks in the design of control and power management unit of HESS. The control strategy for the PSM should consider the extension of the lifespan of the energy storage elements and the protection of the system components from external condition. The selection of appropriate PSM technique confirms the robustness of the system under different applications. It also helps to optimise the sizing of the storage elements (battery and SC).

This section discusses the most common approaches of PSM: low pass filtering [29], first and second rule based approaches [18], [27], [30] followed by the proposed hybrid approach.

A. Low pass filtering (LPF) approach

In this approach, the regulation signal is split into two parts: low and high frequency components that represent, respectively, the battery and the SC reference signals. This approach is very simple to implement, as shown in Fig. 3. However, the design of the cut-off frequency should be carefully chosen as it has impact on the storage sizing of the HESS system. Moreover, the design of the low pass filter should take into

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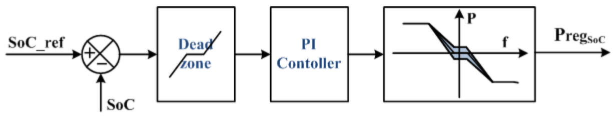
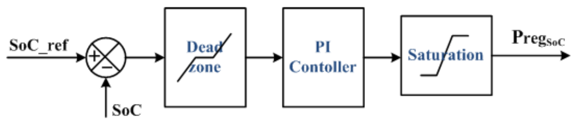


(a)



(b)

Fig. 2. Battery SoC Controller for (a) frequency signal and (b) power signal

account the maximization of the battery lifespan comparing to the huge investment on the short term storage system. As the battery deals with the low frequency reference signals, this approach guarantees that the dynamic stress of the battery is reduced and thus it helps to increase the battery lifetime.

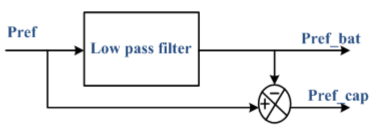


Fig. 3. Low pass filtering approach

For an implementation purposes, a discrete low pass filter ($LPF(z)$) is considered as:

$$LPF(z) = \frac{(1-\alpha)z}{z-\alpha} \tag{8}$$

The filter (8) presents the discrete form of a first order continuous low pass filter ($LPF(p)$), synthesized using a zero-order hold (ZOH) discretezation method as:

$$LPF(p) = \frac{1}{1+\tau p} \tag{9}$$

such that:

$$\alpha = exp\left(\frac{-Ts}{\tau}\right)$$

where T_s is the sampling time.

B. First rule based (FRB) approach

The rule-based approach controls the power exchange of HESS based on rules that are derived from mathematical models and/or human experiences. Rule-based approach is an effective method for real time energy management widely used in HESS applications. The first rule based approach aims to maximize the use of SC within certain voltage range [8]. The maximum and the minimum voltages should be well defined in order to avoid the deterioration of the SC module capacity limit. The flowchart of this method is shown in Fig. 4a.
$V_{cap-min}$ and $V_{cap-max}$ denote respectively, the minimum and the maximum voltages of the SC module.

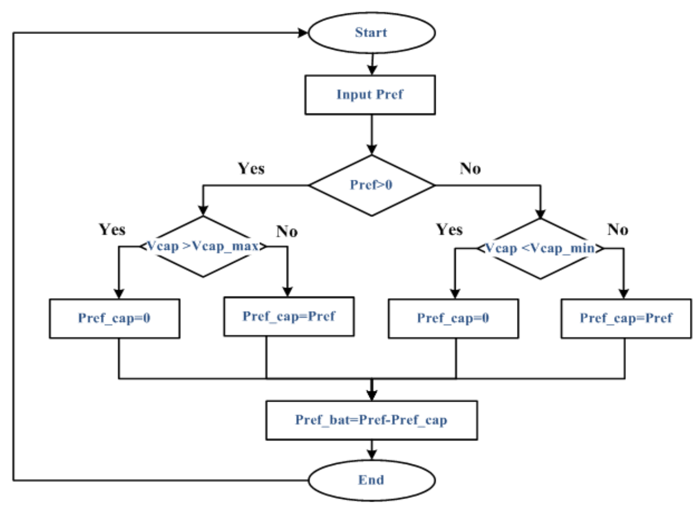
C. Second rule based (SRB) approach

The flowchart of SRB is illustrated in Fig. 4b. Here, the first RB is extended further in the second rule based approach where the PSM includes the power constraint of the SC module depending on its state of charge as well as charge/discharge operation mode. These states and operation modes are derived by the following functions:

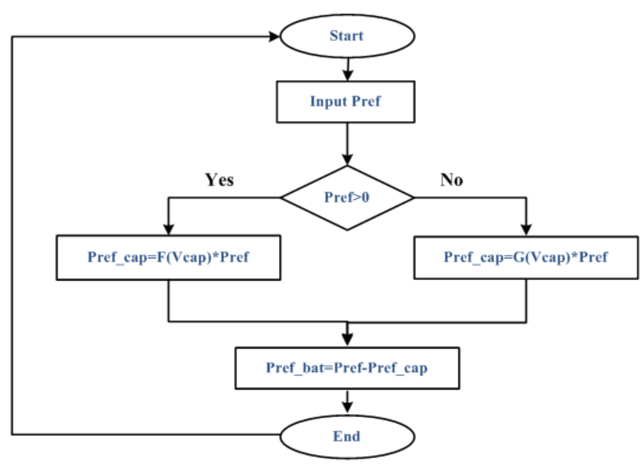
$$F(V_{cap}) = \frac{V_{cap}^2}{V_{ncap}^2} \tag{10}$$

$$G(V_{cap}) = 1 - \frac{V_{cap}^2}{V_{ncap}^2} \tag{11}$$

where V_{cap} and V_{ncap} are respectively, the voltage and nominal voltage of the SC module.



(a) First rule based approach



(b) Second rule based approach

Fig. 4. Flowchart of the rule based approaches

D. Hybrid approach (Hybrid)

The idea of the proposed hybrid approach is to combine the advantages of LPF and first RB approaches. In this approach, battery deals more with the low frequency components and leaves the high frequency compensation for SC. It also helps to avoid the rapid power saturation of the SC comparing to the FRB method so that SC can smoothly support the high frequency components of the regulation signal. The flow chart of this method is given in the Fig. 5.

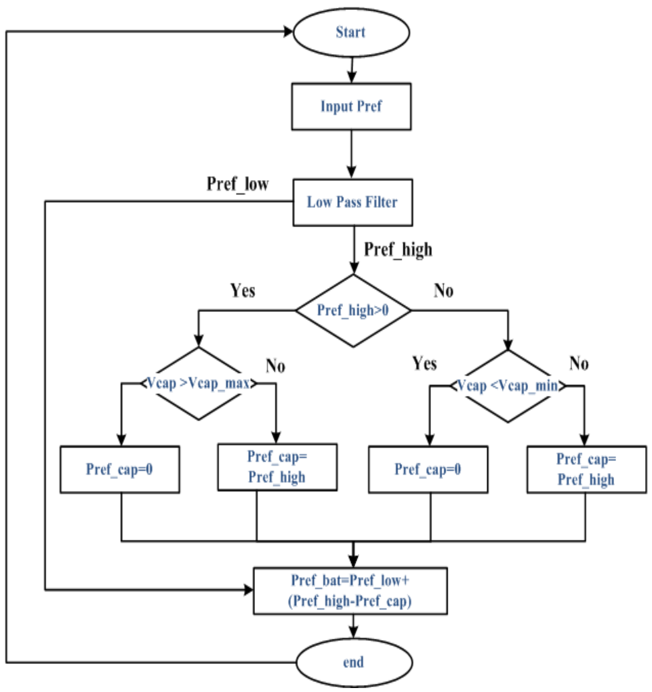


Fig. 5. Flowchart of the hybrid approach

V. Simulation and case studies

The whole system, as shown in Fig.1, is modeled in Matlab SPS. To understand the real performance, the energy loss calculation is also adopted. The self-discharge rates for SC and battery are considered as 30%/day and 10%/month respectively. The life-cycle of the battery and the SC are also considered as 1500 and 500,000 cycles respectively. To be conservative, here the project life time is considered as 25 years and thus this is also the maximum considered lifetime of the battery and SC as well. In that case, SC has to complete more than 50 full cycles per day. It is worth to mention that though the SC has to deal with the fast frequency responses and due to its high life cycle, the lifetime of SC could reach more than 25 years. The other parameters of the power management system are listed in the Table II.

TABLE II
Design parameters of the power management system

P_n	$10MW$
KP_{SoC}	$\frac{C_{bat}}{10MWH}$
KI_{SoC}	0.1
SoC_{ref}	61%
SoC_d	0.5%

A. Case study1: UK (national grid)

UK grid operator wants to enhance the inertial response and improve the rate of change of frequency (ROCOF) index to maintain the system frequency within one percent of 50 Hz at all times, except in abnormal or exceptional circumstances. Therefore, TSO introduces a new dynamic service, termed as EFR, where the active power changes proportionally in response to change in system frequency. In this case study, the UK national grid signal is considered for this newly implemented EFR service.

To generate the reference power signal, the frequency profile of a typical point in the UK network is obtained from [45]. Fig.6a shows the profile for a typical day. This signal is then transferred to the service window [7], to calculate the second-by-second performance measure. The output of this window is the generated main reference signal (in pu), as shown in Fig.6b. The generated reference signal is then divided to

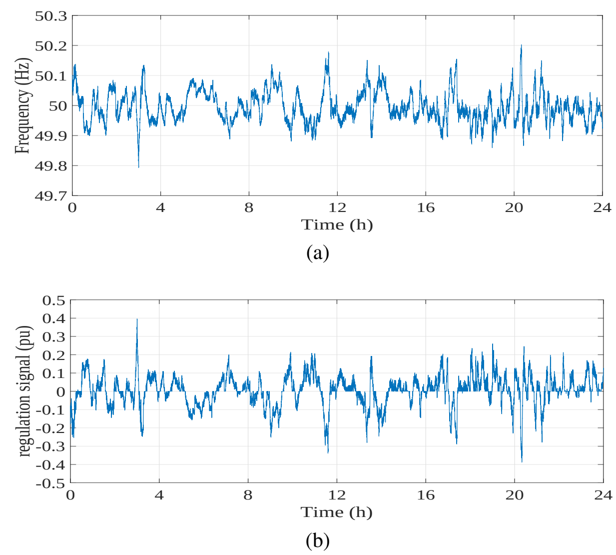


Fig. 6. a) UK grid frequency, 1st Jan 2015[45]; b) Reference power (pu)

the storage elements through the PSM approaches. It is to be noticed that for LPF approach, the coefficients are designed using an adaptive gain such that:

$$\alpha = \alpha_1 + k_\alpha \alpha_2$$

α_1 and α_2 are chosen according to regulation signal characteristic. For this case, $\alpha_1 = 0.984$ and $\alpha_2 = 0.015$. For the hybrid approach, α is chosen to be equal to 0.9999. k_α is designed to increase the power sharing proportionately with the SC capacity.

Fig. 7 shows the impact of the four approaches of PSM on the performance of battery in terms of its effective number of throughput, N_{eff} and lifespan with respect to the capacity percentage of SC (hybridization percentage, p). Fig.7a shows the simulation result of the N_{eff} for the four approaches. It shows that the N_{eff} decreases with the increased capacity of the SC module. It is found that the LPF approach offers the lowest performances. The first and second rule based (FRB, SRB) approaches show almost the same performances for $p < 1.5\%$. However, for the higher hybridization percentage ($p > 1.5\%$), the FRB is more effective and has a good ability to extend the battery lifetime compare to the SRB. In terms of the

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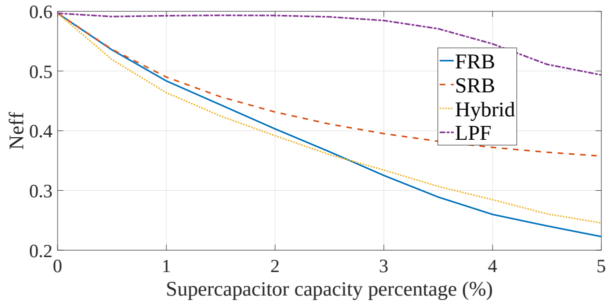
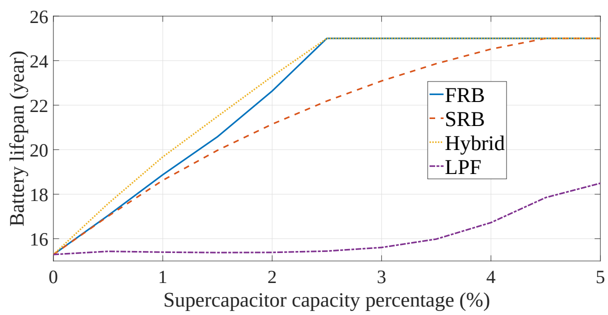
proposed hybrid approach, the best performance is obtained upto the hybridization percentage ($p \leqq 2.5\%$). Above this, the FRB shows the better performances comparing to all other approaches. Fig. 7b presents the battery lifetime conditions



(a) Neff with respect to SC capacity in HESS



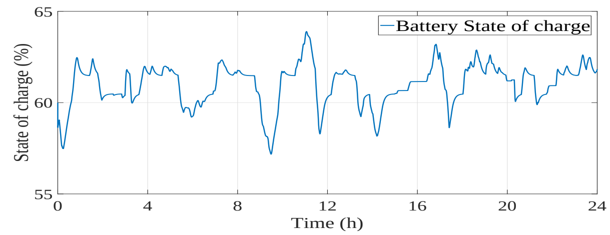
(b) Battery lifespan with respect to SC capacity.

Fig. 7. Performance of PSM on battery lifetime extension, UK grid

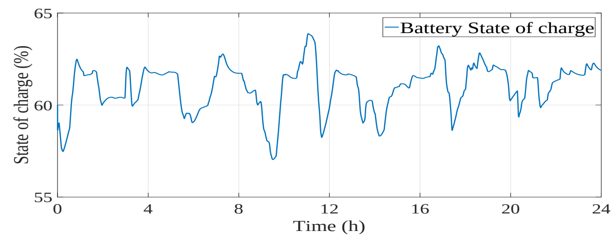
while considering the extension issues described in section 3. The SOC variation range is considered to be 30%, and the maximum life of the battery is fixed to 25 years to account the calendar aging phenomenon. Result shows that the FRB and hybrid approaches have the high impact on the battery lifetime extension for this UK grid service. For both approaches, the battery life can be expanded from 15 to 25 years (around 67%) if the capacity of the SC shares upto 2.5% of the total capacity. If the capacity increases more, it will not have any impact further on the battery life extension.

Fig.8 and 9 show the performances of battery and SC in terms of response (charging/discharging) and power delivery. Results show the cases while using FRB and the hybrid approaches for a value of p=1.5%.

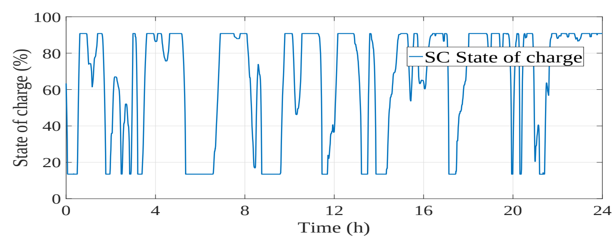
It is also found that, comparing to FRB, the SC is more responsive in hybrid approach, as shown in Fig.8d. It happens due to the addition of high frequency filtration in the hybrid approach. This impacts on the performance of the battery. Fig. 8a, and 8b show the variations of SoC for the battery. Comparing to FRB, the hybrid approach leads to smooth variations of the battery SOC. It helps to reduce the stress in battery and thus extend the lifetime. This justify the previous result in Fig. 7b, which shows that for p=1.5%, the battery lifetime is extended to 20.5 and 21.5 years while HESS considers FRB and hybrid approaches respectively. The power delivery by the battery is shown in Fig 9. Analyzing the battery performance, it is found that in hybrid approach, battery stress decreases in high frequency services and thus it delivers less



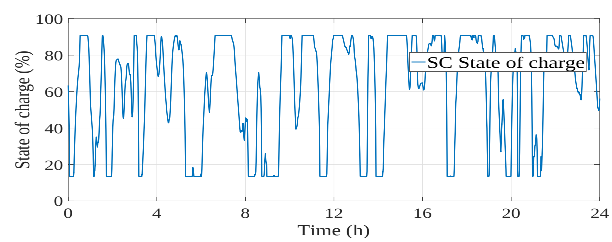
(a) Battery-SOC (FRB)



(b) Battery-SOC (Hybrid)



(c) SC-SOC (FRB)



(d) SC-SOC (Hybrid)

Fig. 8. Performance of FRB and hybrid approaches for p=1.5%: Part 1

power as compare to FRB approach. This performance is observed in Fig. 9a, and 9b.

In order to give further details about the impact of the PSM on system performances, simulation results are presented in Fig.10 for p=2.5%. The battery and SC SOC conditions are shown while using SRB and hybrid approaches respectively. Compare to Fig.10a, Fig. 10b clearly shows the improved SOC management by the battery. Fig. 10c and 10d, verify the performance where it shows that, compare to SRB approach, SC SOC manages more fast frequency stresses using hybrid PSM. Thus, the hybrid approach helps to increase the battery life upto 25 years, as shown in Fig. 7b, whereas using SRB, it goes upto 22 years. Thus Fig. 8, 9 and 10 justify the superiority of the hybrid approach comparing to the FRB and SBR approaches. Indeed, while using the hybrid approach, the SC is more responsive to the high frequency components of the regulation signal. This leads to reduce the battery stress and a smooth control of the battery SOC appears.

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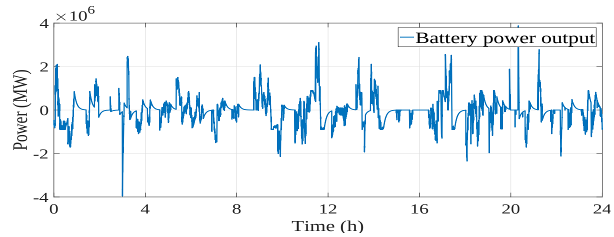
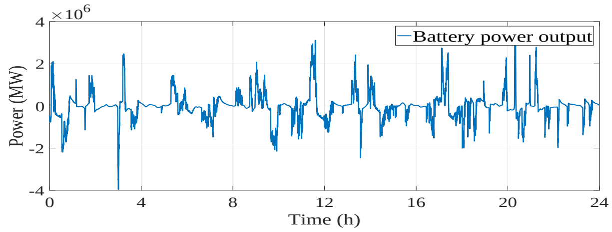
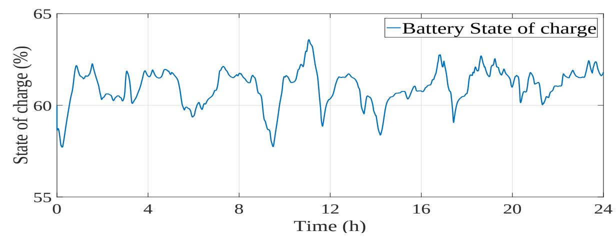


(a) FRB approach

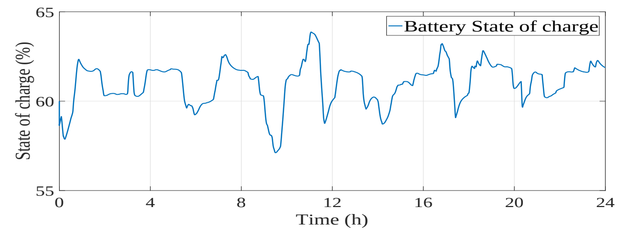


(b) Hybrid approach

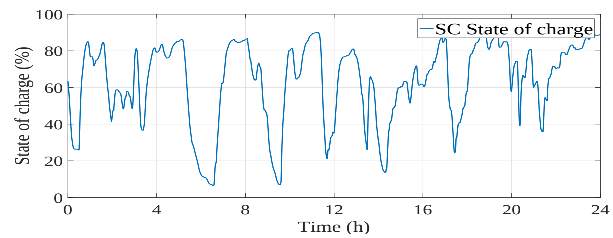
Fig. 9. Power delivery by SC and battery, for p=1.5%: Part 2



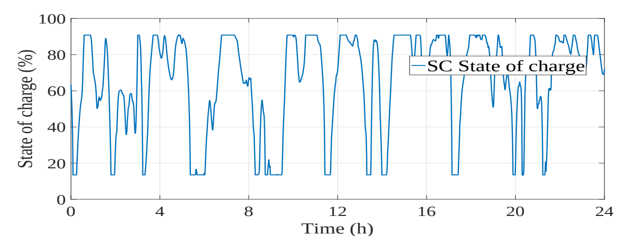
(a) Battery-SOC (SRB)



(b) Battery-SOC (Hybrid)



(c) SC-SOC (FRB)



(d) SC-SOC (Hybrid)

Fig. 10. Performance of SRB and hybrid approaches for p=2.5%

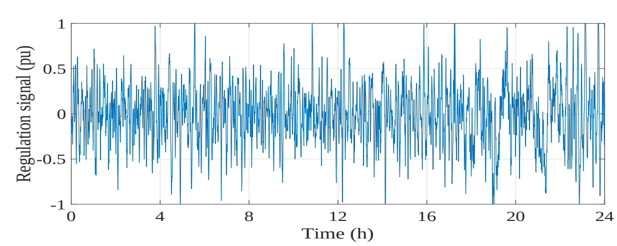


Fig. 11. Regulation signal of PJM (in pu), 5th May 2014

B. Case study2: USA (PJM)

In order to understand more clearly the impact of the PSM on battery life extension for different regulation signals, a second case study is presented here. In this case, a regulation signal for a typical day from the US grid (PJM) [41], as shown in Fig 11 is considered as the required reference signal for the HESS based regulation service provider. This signal is then transferred to the PSM block to analyze the individual performance of battery and SC module. Similar to the first case study, for LPF-PSM approach, LPF gains α_1 and α_2 are chosen as $\alpha_1 = 0.9725$ and $\alpha_2 = 0.025$. In case of hybrid PSM, α is chosen to be equal to 0.9998.

Fig. 12a shows the obtained N_{eff} values while performing simulation for the different approaches of PSM and different values of p. The analysis shows that the considered four approaches of PSM have similar impact as it is found in case study 1 for UK grid. In case of PJM signal, the first approach (LPF) also appears as the least effective method. Comparing to LPF, the second rule based (SRB) technique exhibits more ability to reduce the impact of regulation signal on battery degradation. It should be mentioned that the decreasing slope of N_{eff} is more important for a small value of p ($p \leq 1.5\%$) which represents that the selected approach is more effective for a small value of hybridization capacity. Comparing to all, the first rule based (FRB) and the proposed hybrid approach show the best performance. It is found that, for both of these techniques, the increasing value of p has a great impact on the number of effective throughput cycle. For both cases, N_{eff} values are nearly same and it indicates that both PSMs are suitable for PJM dynamic regulation service.

Fig. 12b presents the lifespan estimation of the battery using the obtained results and the described degradation model in section 3.2.1 as well as the same operating condition described in the case study 1. LPF approach has the minor impact on extending the battery lifetime. The SRB approach can only extend the battery life up to about 12 years. The best responses are obtained from FRB and hybrid approaches. The result shows that both approaches could extend the battery lifespan up to 25 years for a hybridization percentage $p \geq 2\%$. This value is align with one given in [8] where the HESS offers the maximum benefit.

C. Discussion

In both case studies, it is found that the performance of PSM depends on the required service for the regulation signal and the hybridization factor (SC capacity) of the HESS.

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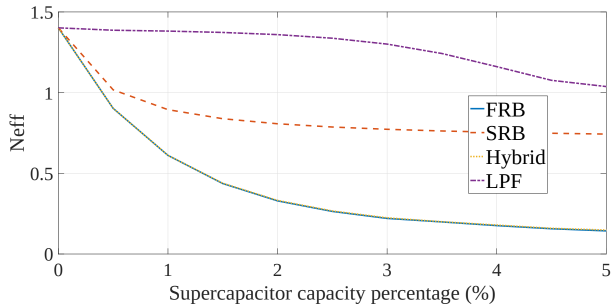
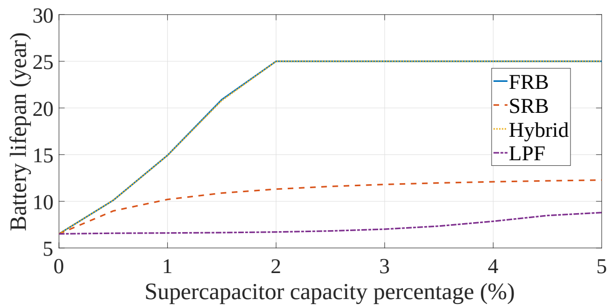


(a) Effect of PSM on the Neff with respect to SC capacity in HESS



(b) Effect of PSM on battery lifespan with respect to SC capacity in HESS.

Fig. 12. Performance of PSM on battery life extention, US grid

Result shows that LPF and SRB approaches should not be a good choice for HESS to provide grid ancillary services such as EFR, FFR etc. Depending on the regulation signal and required service, FRB and hybrid approaches should be preferable. Hybrid approach shows comparatively better performance for UK grid, whereas for US grid, both are same. The effective capacity of the SC also depends on the regulation signal and the applied PSM. Considering the project and maximum possible battery lifetime upto 25 years, the effective SC capacity is also found maximum 2.5% and 2.0% of the HESS capacity for the UK and US grid respectively. In case of UK grid, SRB approach can also extend the battery life upto 25 years by the support of 4.5% of SC capacity. In that case, the total cost of the system will increase and thus may not be a financially viable solution. Thus, the choice of regulation signal and service, the selection of PSM approach and the financial mechanism will ultimately help to optimise the SC capacity as well as extend the battery lifetime of the service provider (HESS). Fig. 13 illustrates this relationship to understand the impact of PSM where the green line arrows indicate the process to extend/maximise the battery life and optimise SC to achieve a sustainable HESS for grid ancillary services.

Taking into consideration the aforementioned remark and observation, it is recommended that for each regulation signal, an extensive analysis and investigation should be carried out to chose the most effective associated PSM approach that will assist to optimize the SC capacity and enable expending the battery life span and maximizing the techno-economic benefits. The application of HESS for fast frequency grid services are relatively new and now-a-days research and demonstration are being carried on and more to be done. As the regulation signal, the required services and response time vary from network to network, from the technical point of view, it is very challenging also to design the appropriate hybrid DC/AC converter (active/passive) for all network. Also the converter response/performance is somehow depends on the type of storage system. Also the economic sustainability of the HESS depends on the cost of energy storage system including their life time and dynamic characteristics. A thorough comparative study on different types of HESS solution for different network is also very important. A follow-up paper will also discuss part of the details of techno-economic analysis and sustainability studies of this research.

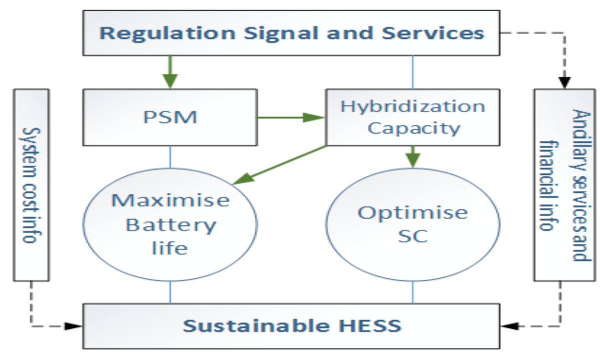


Fig. 13. Relationship of PSM with battery life and SC capacity

VI. Conclusion

In this paper, the impact of power sharing method on the battery life extension in a full active parallel HESS is analyzed to provide the grid ancillary services. Analysis has been extended for two different types of grid signal, taken from two regions of the world: UK (national grid, for EFR service) and US (PJM, for FFR service). Four approaches of PSM (LPF, FRB, SRB, proposed Hybrid) are applied to understand their impacts on the battery life extension for these special grid services. It is found that, except LPF, all other approaches have great impact on the extension of the battery life. For both type of signal, LPF is least effective and SRB has moderate impact. The best results are found for the FRB and the proposed hybrid approaches. The hybrid approach shows a degree of better performance for UK grid while the sharing capacity of SC is kept low ($\leqq 2.5\%$). For the HESS with higher sharing of SC module, FRB could be the best option, but this depends on the economic analysis as well which is beyond this study. For US grid, this SC sharing ($\leqq 2.0\%$) of the HESS capacity should be good enough to provide FFR service with maximise the battery life time. It can be concluded that the service providers should design their HESS system based on the signal characteristics and required services, considered PSM and then define the SC sharing capacity to reduce the stress on the battery. It is found that both PSM approaches (first rule based and proposed hybrid) and the regulation signal dynamics have huge influence on the performances of the implemented power management system and its ability to extend the battery lifespan.

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